

BACKWARD ELASTIC p^3He SCATTERING AT ENERGIES 1 - 2 GeV

L.D. Blokhintsev,¹ A.V.Lado,² Yu.N. Uzikov ³

*Laboratory of Nuclear Problems, Joint Institute for Nuclear Research, Dubna, Moscow
reg., 141980 Russia*

Abstract

The two-body transfer amplitude for the rearrangement process $i + \{jkl\} \rightarrow j + \{ikl\}$ is constructed on the basis of technique of 4-dimensional covariant nonrelativistic graphs. The developed formalism is applied to describing backward elastic p^3He scattering in the energy range $0.5 \div 1.7$ GeV. Numerical calculations performed using the 5- channel wave function of the 3He nucleus show that the transfer of a noninteracting np- pair dominates and explains satisfactorily the energy and angular dependence of the differential cross section at energies $0.9 \div 1.7$ GeV. A weak sensitivity to high momentum components of the 3He wave function in spite of large momentum transfer as well as a very important role of rescatterings in the initial and final states are established.

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¹Institute of Nuclear Physics, Moscow State University, 119899 Moscow ,Russia

²Department of Physics, Kazakh State University, Timiryazev Str., 47, 480121 Alma-Ata, Kazakhstan

³*e-mail address:* uzikov@nusun.jinr.dubna.su FAX: (7) 09621 66666

The most interesting peculiarity of the backward elastic $p\ ^3He$ scattering at energies $0.5 \div 1.5$ GeV is the large momentum transfer $\Delta = 2 \div 3$ GeV/c [1]. This value of Δ is considerably larger than the Δ value reached in the experiments with electron scattering from the 3He nucleus and therefore one can hope to obtain an important new information about the structure of 3He at short distances between nucleons $r_{NN} \sim 1/\Delta$ from the $p\ ^3He$ scattering experimental data. Simple models of the $p\ ^3He \rightarrow ^3He p$ process like deuteron (d) and singlet deuteron (d^*) exchanges suggested previously in Refs. [2]- [6] are in agreement with this point of view and lead to the conclusion that the differential cross section of backward elastic p^3He -scattering at initial energies 1-2 GeV [1] "measures" the high momentum components of 3He wave function (w.f.) in the configurations $^3He \rightarrow d + p$, $^3He \rightarrow d^* + p$. According to Ref. [6], the momentum distributions in these channels, obtained from the experimental data on inclusive reactions $^3He A \rightarrow p(0^\circ)X$ and $^3He A \rightarrow d(0^\circ)X$, are quite compatible with those from the $p\ ^3He \rightarrow ^3He p$ process. However, the main drawback of the papers [2] - [6] is the use of the two-body approximation for the 3He nucleus structure and the neglect of initial and final state interactions in [6]. As shown here (see [7]), the relation between the full three-body wave function of the 3He nucleus and the cross section of the $p\ ^3He \rightarrow ^3He p$ process is nontrivial mainly due to three-body structure of 3He and Glauber rescatterings in the initial and final states. We found that the deuteron and singlet deuteron exchanges are negligible as compared to the noninteracting np-pair exchange which allows to explain the available experimental data at $T_p \sim 0.9 - 1.7$ GeV without involving high momentum components of the 3He w.f.

We proceed from the technique of covariant 4-dimensional (nonrelativistic) Feynman graphs [8]. The dominating mechanism displays weak sensitivity to the relativistic effects. For this reason the use of the nonrelativistic technique is valid. When processes involving three-body bound states $\{ijk\}$ are considered, the main element of this approach is the amplitude of the virtual decay of such a state into three particles $\{ijk\} \rightarrow i + j + k$. The simplest analytical behaviour is manifested by the truncated part of this amplitude, $R^{ij}(\mathbf{q}_{ij}, \mathbf{Q}_k, E_{ij})$, which is the sum of those graphs which end in the interaction between particles only with indices i and j . Here \mathbf{q}_{ij} and E_{ij} are the momentum and energy of relative motion in the ij pair respectively, \mathbf{Q}_k is the momentum of the nucleon spectator k in the center-of-mass system (c.m.s.) of $\{ijk\}$ nucleus. The properties of vertex functions R^{ij} and corresponding integral equations are presented in Ref. [8]. The most general formula for the two-nucleon transfer amplitude in the process $4 + \{123\} \rightarrow 1 + \{423\}$ is given by the sum of graphs in Fig.1. The graph a in Fig.1 describes the transfer of two noninteracting nucleons with numbers 2 and 3. The second graph (b) in Fig.1 describes the interacting pair transfer (IPT), which contains the deuteron and singlet deuteron

exchanges. After performing the integration over relative energy of the transferred pair E_{23} , the first term transforms to the infinite series of 3-dimensional graphs. In the Born approximation the sum of graphs in Fig.1 can be written as

$$T_B = 6(2\pi)^{-3} \int d^3q_{23} (\varepsilon + \mathbf{q}_{23}^2/m + 3\mathbf{Q}_1^2/4m) \chi_{p'}^+(1) \{ \varphi_f^{23+}(4; 23) \varphi_i^{31}(2; 31) \\ + \varphi_f^{42+}(3; 42) \varphi_i^{31}(2; 34) + \varphi_f^{34+}(2; 34) \varphi_i^{31}(2; 31) \} \chi_p(4), \quad (1)$$

where $\varphi^{ij}(k; ij) = \varphi^{ij}(\mathbf{q}_{ij}, \mathbf{Q}_k)$ is the Faddeev component of the full 3He wave function [11] $\Psi_{\{123\}} = \varphi^{12} + \varphi^{23} + \varphi^{31}$ (the lower indices i and f denote the initial and final states respectively); $\chi_p(1)$ and $\chi_p(4)$ are the spin-isospin wave functions of the protons; ε is the binding energy of 3He nucleus and m denotes the nucleon mass. The terms $\varphi^{23+}\varphi^{31}$, $\varphi^{42+}\varphi^{31}$, $\varphi^{34+}\varphi^{31}$ correspond to the IPT, sequential transfer (ST) in the Born approximation and nonsequential transfer (NST) amplitudes respectively.

The most important feature of the integral (1) is the following. The term $\varphi_f^{42+}\varphi_i^{31}$ in the integrand of Eq. (1), which is responsible for the dominating ST contribution, has the following structure of arguments

$$\varphi_f^{42+}\varphi_i^{31} = \varphi_f^{42+} \left(-\frac{1}{2}\mathbf{q}_{23} - \frac{3}{4}\mathbf{Q}_4, \mathbf{q}_{23} - \frac{1}{2}\mathbf{Q}_4 \right) \\ \times \varphi_i^{31} \left(-\frac{1}{2}\mathbf{q}_{23} + \frac{3}{4}\mathbf{Q}_1, -\mathbf{q}_{23} - \frac{1}{2}\mathbf{Q}_1 \right). \quad (2)$$

The remaining two terms corresponding to the NST and IPT mechanisms have the forms

$$\varphi_f^{34+}\varphi_i^{31} = \varphi_f^{34+} \left(-\frac{1}{2}\mathbf{q}_{23} + \frac{3}{4}\mathbf{Q}_4, -\mathbf{q}_{23} - \frac{1}{2}\mathbf{Q}_4 \right) \\ \times \varphi_i^{31} \left(-\frac{1}{2}\mathbf{q}_{23} + \frac{3}{4}\mathbf{Q}_1, -\mathbf{q}_{23} - \frac{1}{2}\mathbf{Q}_1 \right), \quad (3)$$

$$\varphi_f^{23+}\varphi_i^{31} = \varphi_f^{23+}(\mathbf{q}_{23}, \mathbf{Q}_4) \varphi_i^{31} \left(-\frac{1}{2}\mathbf{q}_{23} + \frac{3}{4}\mathbf{Q}_1, -\mathbf{q}_{23} - \frac{1}{2}\mathbf{Q}_1 \right). \quad (4)$$

At the scattering angle $\theta_{c.m.} = 180^\circ$ we get $\mathbf{Q}_4 = -\mathbf{Q}_1$. Under this condition Eq. (2) differs from Eqs. (3) and (4) in that two of four momenta can simultaneously become equal to zero at integration over \mathbf{q}_{23} (for example, at the point $\mathbf{q}_{23} = 3/2\mathbf{Q}_1$ one has $-1/2\mathbf{q}_{23} - 3/4\mathbf{Q}_4 = 0$ and $-1/2\mathbf{q}_{23} + 3/4\mathbf{Q}_1 = 0$). In Eqs. (3) and (4) only one momentum can be equal to zero while the other three have the values $\sim |\mathbf{Q}_1| = |\mathbf{Q}_4|$. In the kinematic region $T_p = 0.7 - 1.7 \text{ GeV}$ the momenta $|\mathbf{Q}_1|$ and $|\mathbf{Q}_4|$ have rather large values $\sim 0.5 \text{ GeV}/c$. One can conclude from this that term (2) makes the dominating contribution to the integral (1) since the functions $\varphi^{ij}(\mathbf{q}, \mathbf{Q})$ decrease fast with increasing $|\mathbf{q}|$ or $|\mathbf{Q}|$. Numerical calculations are performed using Faddeev 3He w.f. from [9, 10] for NN-potential in 1S_0 and $^3S_1 - ^3D_1$ states in the RSC form. This wave function consists of 5 channels for each Faddeev component φ^{ij} . As shown in Fig.2, in the region

$T_p = 1 - 1.7 \text{GeV}$ the ST contribution is by factor $\sim 30 - 40$ higher in comparison with the experimental data and by 3-4 orders of magnitude larger than the IPT and NST-contributions. At $\theta_{c.m.} < 180^\circ$ the ST amplitude loses this advantages and as a result its contribution decreases very fast with increasing the difference $|180^\circ - \theta_{c.m.}|$, whereas the experimental angular dependence of the cross section is smooth (Fig.3).

Taking into account the rescatterings in the initial and final states of the process $p^3\text{He} \rightarrow ^3\text{He}p$ in the framework of diffraction multistep theory of Glauber-Sitenko [12], we find for the np transfer amplitude the following expression

$$\begin{aligned} T_{fi}^{dist} = & T_B(\mathbf{p}'_\tau, \mathbf{p}'_p; \mathbf{p}_\tau, \mathbf{p}_p) + \frac{i}{4\pi p_p} \int d^2q F_{p\tau}(\mathbf{q}) T_B(\mathbf{p}'_\tau, \mathbf{p}'_p; \mathbf{p}_\tau + \mathbf{q}, \mathbf{p}_p - \mathbf{q}) \\ & + \frac{i}{4\pi p'_p} \int d^2q' f_{pp}(\mathbf{q}') T_B(\mathbf{p}'_\tau - \mathbf{q}', \mathbf{p}'_p + \mathbf{q}'; \mathbf{p}_\tau, \mathbf{p}_p) \\ & - \frac{1}{(4\pi)^2 p'_p p_p} \int \int d^2q d^2q' F_{p\tau}(\mathbf{q}) f_{pp}(\mathbf{q}') T_B(\mathbf{p}_\tau - \mathbf{q}', \mathbf{p}'_p + \mathbf{q}'; \mathbf{p}_\tau + \mathbf{q}, \mathbf{p}_p - \mathbf{q}); \end{aligned} \quad (5)$$

here the amplitude T_B is defined by Eq. (1) and the amplitudes $F_{p\tau}(\mathbf{q})$ and $f_{pp}(\mathbf{q})$ describe the forward elastic $p^3\text{He}$ and pp -scattering, respectively, at the transferred momentum \mathbf{q} ; \mathbf{p}_τ and \mathbf{p}_p (\mathbf{p}'_τ and \mathbf{p}'_p) are the c.m.s momenta of initial (final) ^3He nucleus and proton, respectively.

On the basis of Eq. (5) we found that (i) the absolute value of the differential cross section at $\theta_{c.m.} = 180^\circ$ decreases considerably due to rescatterings and as a result agrees satisfactorily with the experimental data at $T_p = 0.7 - 1.7 \text{GeV}$ [1] (Fig.2); (ii) the angular dependence becomes very smooth in the range $\theta_{c.m.} = 160^\circ - 180^\circ$ in qualitative agreement with the experimental data (Fig.3). The cross section at $\theta_{c.m.} = 180^\circ$ decreases due to the imaginary part of the elastic pN - scattering amplitude, which takes into account the coupling to inelastic channels. As shown recently in Ref. [14], the suppression factor caused by rescatterings in the framework of the same method is about $\sim 2 - 3$ for the one-nucleon exchange mechanism of the process $pd \rightarrow dp$. The smooth angular dependence comes from the fact that due to rescatterings the effective arguments of the w.f. of ^3He in the integrals (5) decrease in the upper and the lower vertices simultaneously [14]. Weak sensitivity of the dominating ST- mechanism to the high momentum components of ^3He w.f. is manifested by (i) the nonimportant contribution of D-components of w.f. at $T_p > 1 \text{GeV}$ (see Fig.2) and (ii) very small enhancement of the cross section after substitution of Lorenz-invariant momenta $\mathbf{q}_{ij} \mathbf{Q}_k$ into the amplitude T_B instead of nonrelativistic ones. From the other hand, both the D-component of the ^3He w.f. and relativistic effects are very important for the mechanism of deuteron exchange. However the role of that mechanism is negligible.

In conclusion, an unexpected feature of process $p^3He \rightarrow^3 Hep$ at $T_p = 1 - 1.7GeV$ is established, namely, a weak sensitivity of the dominating ST mechanism to high momentum components of 3He wave function in spite of large momentum transfer. It should be noted that the ST amplitude reduces exactly to zero if the component $\hat{A}\{NN(^1S_0) + N\}$, where \hat{A} is the antisymmetriser, is excluded from the 3He w.f. According to the definition in work [10], it corresponds to the channel with number $\nu = 1$. Consequently the cross section of the process $p^3He \rightarrow^3 Hep$ at $\theta_{c.m.} = 180^\circ$ measures the weight of this channel [13]. Faddeev calculations [15] predict that the ground state spin of the 3He nucleus is dominated by the neutron just due to this component of the 3He w.f. Therefore it is of great interest to perform the experimental investigation of spin observables in this process at energies $T_p > 1GeV$.

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Figure captions

Fig.1. Two-particle transfer amplitude of the $4 + \{123\} \rightarrow 1 + \{423\}$ process in terms of 4-dimensional graphs: a – the noninteracting pair transfer,

b – the interacting pair transfer (IPT),

c – total amplitude; $R'_i = R_i^{12} + R_i^{31}$, $R'_f = R_f^{42} + R_f^{34}$, $R_i = R_i^{12} + R_i^{31} + R_i^{23}$

Fig.2. The differential cross section of the elastic p^3He scattering in the c.m.s. at $\theta_{c.m.} = 180^\circ$ as a function of initial proton energy T_p and transferred momentum Δ . The curves are the results of calculations (curves 1 – 5 correspond to the Born approximation): 1 – IPT (S) with S component of the 3He w.f., 2 – NST (S), 3 – ST (S), 4 – IPT (S+D), 5 – ST (S+D); 6 – ST (S) taking into account rescatterings. The dots denote the data from Ref.[1].

Fig.3. The differential cross section of the p^3He elastic scattering into backward hemisphere at different initial energies (MeV) shown near the curves. The curves are the results of calculations using IPT+NST+GST mechanism in the S-wave approximation for the 3He wave function: the dashed curves are obtained in the Born approximation and the full curves are obtained taking into account Glauber rescatterings; p is the c.m. momentum of the proton, $\theta_{c.m.}$ is the scattering angle. The experimental dots are from Ref. [1].

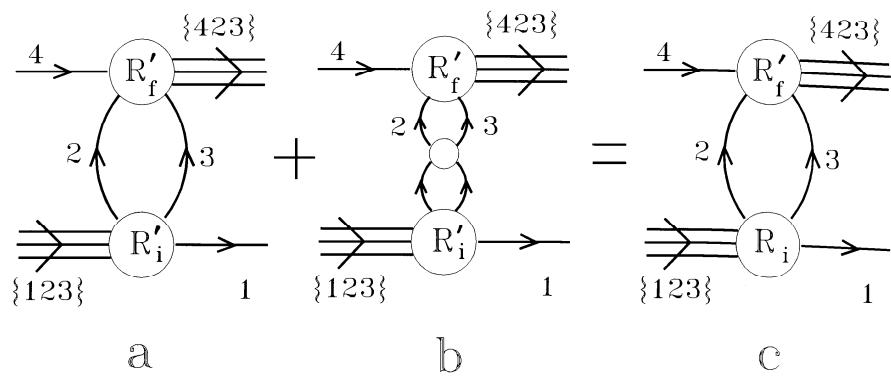


Figure 1:

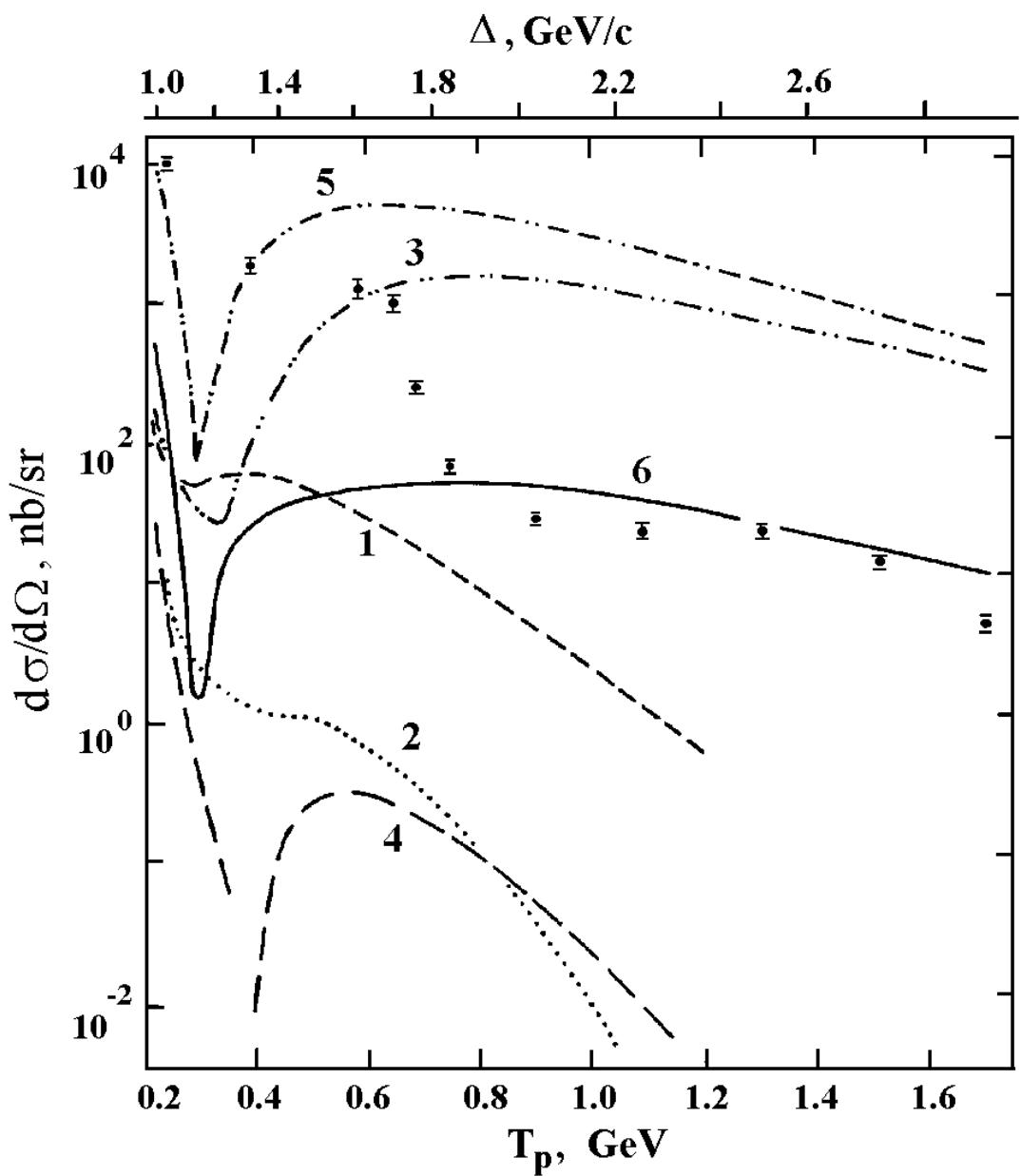


Figure 2:

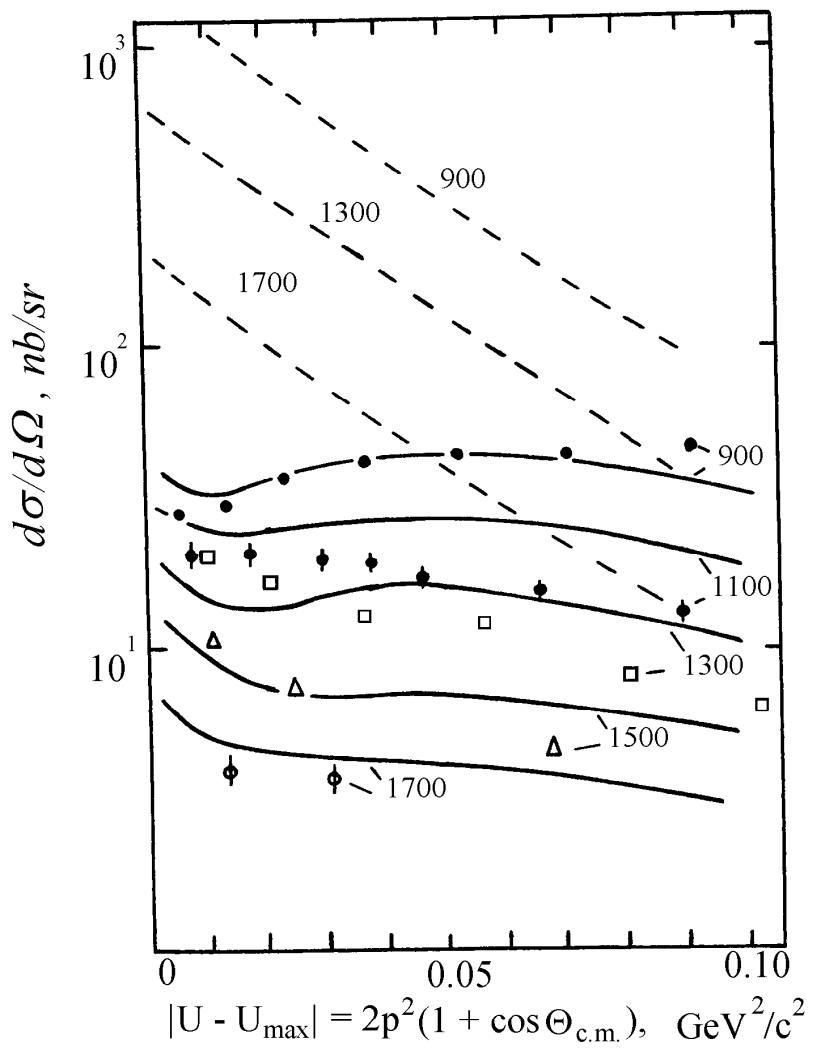


Figure 3: